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Interceptor Small Arms Protective Insert (SAPI) MANTECH Product Enhancement Test Report I

by Jeffrey A. Mears, Robert F. Monks, Robert Wolffe, and James F. Mackiewicz

ARL-CR-487 February 2002

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Natick, MA 01760-5011

under contract

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Abstract

This report summarizes the work performed by Specialty Plastics Products of Pennsylvania Inc. and their subcontractor, Simula Safety Systems Inc., under the Manufacturing Technology (MANTECH) program sponsored by the U.S. Army Materiel Command and executed by the U.S. Army Natick Soldier Center. The objective of this effort was to investigate armor materials and processes that could potentially provide cost reductions to the multi-Service Interceptor Small Arms Protective Inserts (SAPI).

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1. Introduction

As described in U.S. Army Materiel Command Acquisition Center (USAMCAC) Contract No. DAAN02-98-D-5007-003, line item 0004, Manufacturing Technology (MANTECH) statement of work, the contractor shall investigate materials and material processes that will potentially provide cost reduction benefits to the U.S. Marine Corps and the U.S. Army. The scope of work included the following tasks:

- Fabricate and ballistically test at least five small arms protective insert (SAPI) products with cost-reduction composite materials. The composite backing systems will be fabricated in conjunction with the currently used Spectra Shield (SS) composite backing in an array configuration to be determined by the contractor. The lower-cost fiber reinforced plastic (FRP) materials to be experimentally tested will include Kevlar 49 and Kevlar 29 (KRP), glass-reinforced plastic (GRP), and Spectra-reinforced plastic (SRP).
- Investigate SAPI fabrication parameters, which shall expeditiously process the greatest number of quality inserts per run. Processing parameters for investigation shall include time, temperature, pressure, and volume. Evaluation of the most efficient combination of parameters shall be validated through Government nondestructive analysis and ballistic testing.
- Coordinate with Government personnel (U.S. Army Natick Soldier Center, U.S. Army Aberdeen Test Center [ATC], and U.S. Army Research Laboratory [ARL]) to correlate nondestructive prototype confirmation testing to reduce the costs associated with ballistic destructive testing. If feasible, implement nondestructive production lot acceptance testing as part of cost-reduction acceptance criteria.
- Submit findings of the previously mentioned tasks, and any additional tasks that are paid for by MANTECH funds under this delivery order, in a final report to the project officers. The final report shall be submitted in the contractor's format and must be delivered within 30 days of completion of MANTECH studies under this delivery order. All efforts under this delivery order and the submittal of the final report must occur no later than 1 December 1999.
- The final report shall be submitted to the project officers via e-mail in Microsoft Word 6.0 or higher.

This document will summarize the efforts involved in developing the design to meet the current Interceptor SAPI requirements.

2. SAPI First Article Test (FAT) Optimization Testing

The following testing was accomplished in an attempt to optimize the SAPI design in order to meet or exceed the FAT requirements outlined in the SAPI performance specification. These tests were performed in February–April 1999.

2.1 Quasi-Isotropic Laminate

It has been shown in some of the soft body armor work, that by alternating the ply orientation between 0°, 90°, +45°, and -45° increased ballistic performance can be achieved. We fabricated six specimens of 0.210-in tile with 46 plies SS in a quasi-isotropic layup. The targets had an areal density of 3.95 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 1.

Table 1. V_{50} testing with 46-ply 0/+45/-45 SS backings.

Shot No.	Velocity (fps)	Result
1	2885	CP
2	2899	CP
3	2748	CP
4	2699	CP
5	2568	PP

Notes: CP = complete penetration.
PP = partial penetration.

The 46-ply quasi-isotropic SS test series resulted in a V_{50} of 2633 fps (2 shot) with a 131-fps spread. This was below the acceptable V_{50} requirement; therefore, this laminate design was not considered for further testing.

2.2 Fiberglass/SS Hybrid Laminate

It has been shown in metal/composite armor system testing that adding 1 ply of fiberglass between the metal and SS improves the ballistic performance. We fabricated six specimens of 0.210-in tile with 1 ply of fiberglass/epoxy and 42 plies of SS. The targets had an areal density of 4.03 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 2.

Table 2. V_{50} testing with 42-ply SS/1-ply fiberglass backings.

Shot No.	Velocity (fps)	Result
1	2887	CP
2	2854	PP
3	2855	PP
4	2969	CP
5	2948	CP
6	2929	PP

The 42-ply SS/1-ply fiberglass test series resulted in V_{50} of 2907 fps (6 shot) with a 115-fps spread. The addition of the fiberglass produced marginal improvements with an increase in the material cost and plate complexity; therefore, this laminate design was not considered for further testing.

2.3 Kevlar/SS Hybrid Laminate

Past ballistic data indicate that a hybrid of Kevlar and SS will increase ballistic performance. We fabricated six specimens of 0.210-in tile with 1 ply of Kevlar/epoxy and 44 plies of SS. The targets had an areal density of 4.04 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 3.

Table 3. V_{50} testing with 44-ply SS/1-ply Kevlar backings.

Shot No.	Velocity (fps)	Result
1	2843	PP
2	2977	PP
3	3050	PP
4	3097	CP
5	3061	PP
6	3075	PP

The 44-ply SS/1-ply Kevlar test series resulted in a V_{50} of 3086 fps (2 shot) with a 22-fps spread. The addition of the Kevlar produced an improvement in the V_{50} performance; therefore, this laminate design was considered for further testing.

2.4 Kevlar/SS Hybrid Laminate V_0 Testing

In order to evaluate the Kevlar/SS hybrid laminate, we prepared five SAPI plates using production tiles (0.210 in minimum) with the 1-ply Kevlar and 46 plies of SS. The plates had a nominal areal density of 4.10 psf (without durability covers). The results for this series are shown in Table 4.

Table 4. V_0 threat A FAT preparation (Kevlar hybrid).

Sample No.	Velocity (fps)	Obliquity (°)	Result	BFD (in)
1	2787	0	PP	1.38
1	2780	0	PP	1.38
1	2796	30	PP	1.25
2	2763	0	PP	1.38
2	2786	0	CP	N/A
2	2797	30	PP	1.38
3	2796	0	PP	1.60
3	2795	0	PP	1.70
3	2781	30	PP	1.40
4	2639	0	PP	1.38
4	2777	0	PP	1.62
4	2767	30	PP	1.38
5	2785	0	PP	1.50
5	2787	0	CP	N/A

Notes: BFD = back face deformation.
N/A = not applicable.

As shown in Table 4, this design resulted in two complete penetrations (2786 fps and 2787 fps) which would not satisfy the performance requirements; therefore, additional testing was required.

2.5 Graphite/SS Hybrid Laminate

After discussions with Simula Safety Systems Inc. (Simula)* we concluded that we should investigate the use of graphite/epoxy† as a hybrid material with the SS PCR material. The graphite/epoxy is much stiffer than either the fiberglass or the Kevlar/epoxy and as such will provide more support to the ceramic tile during the ballistic impact event. We fabricated six specimens of 0.210-in tile with a ply of graphite/epoxy and 44 plies of SS. The targets had an areal density of 4.03 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 5.

Table 5. V_{50} testing with 44-ply SS/graphite hybrid backings.

Shot No.	Velocity (fps)	Result
1	2902	PP
2	2943	PP
3	3051	PP
4	3062	CP
5	3061	PP
6	3133	CP

The 44-ply SS/graphite hybrid test series resulted in a V_{50} of 3076 fps (4 shot) with an 82-fps spread. This result was similar to the V_{50} that was obtained using the Kevlar/SS hybrid laminate. Due to the expensive nature of the graphite/epoxy material, we decided to look at other alternatives for armor system designs.

2.6 SS Plus Laminate

Honeywell supplied samples of SS PCR Plus,‡ which they report exhibits increased ballistic performance over standard SS PCR.‡ We fabricated six specimens of 0.210-in tile with 61 plies of SS PCR Plus. The targets had an areal density of 4.09 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 6.

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*Simula Safety Systems Inc., Applied Technology Division, 7822 S. 46th Street, Phoenix, AZ 85044.

†Simula Product No. (P/N) 102906-2HL.

‡SS PCR and SS PCR Plus are Honeywell Company registered tradenames for types of Spectra Shield ballistic laminates.

Table 6. V_{50} testing with 61-ply SS Plus backings.

Shot No.	Velocity (fps)	Result
1	2868	PP
2	2945	CP
3	2934	PP
4	2953	PP
5	2940	PP
6	3011	PP

The 61-ply SS Plus test series resulted in a V_{50} of 2978 fps (2 shot) with a 66-fps spread. The change to SS Plus produced marginal improvements, with an increase in the material cost and plate complexity; therefore, this laminate design was not considered for further testing.

2.7 Thicker Tile/Standard Laminate

We investigated an increased areal density armor system to see how performance would be affected. We looked at thicker tile with the same laminate and fabricated six specimens of 0.250-in tile with 43 plies of SS PCR. The targets had an areal density of 4.47 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 7.

Table 7. V_{50} testing with thicker tile and standard laminate.

Shot No.	Velocity (fps)	Result
1	2836	PP
2	2953	PP
3	2999	PP
4	3142	CP
5	3110	PP
6	3158	CP

The thicker tile/standard laminate test series resulted in a V_{50} of 3150 fps (2 shot-reverse) with a 16-fps spread. While this armor system produced a good V_{50} value, we did not have authorization to increase the areal density of the SAPI system at this time, so this design was no longer considered.

2.8 Warp-to-Fill Laminate

We investigated the effect of how the laminate is laid up prior to autoclave cure. The supplier of the SS material, Allied Signal, specified that the material be laid up warp face to fill face (where every ply is laid on the previous ply just as it is oriented on the roll) prior to autoclave or press cure. We fabricated six specimens of 0.210-in tile with 43 plies of SS PCR warp face to fill face. The targets had an areal density of 3.95 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 8.

Table 8. V_{50} testing with warp face to fill face laminate.

Shot No.	Velocity (fps)	Result
1	2857	PP
2	2958	CP
3	2864	PP
4	2934	PP
5	2942	PP
6	2951	PP

The warp face to fill face laminate test series resulted in a V_{50} of 2954 fps (2 shot) with a 7-fps spread. This result was consistent with the baseline test results.

2.9 Fill-to-Fill Laminate

We wanted to see how the test results would vary from the previous test series if the laminates were laid up fill face to fill face (where every other ply is flipped). We fabricated six specimens of 0.210-in tile with 43 plies of SS PCR fill face to fill face. The targets had an areal density of 3.95 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 9.

The fill face to fill face laminate test series resulted in a V_{50} of 2940 fps (4 shot) with a 37-fps spread. This test indicated that the layup sequence has no effect on the ballistic performance of the armor system.

Table 9. V_{50} testing with fill face to fill face laminate.

Shot No.	Velocity (fps)	Result
1	2816	PP
2	2960	CP
3	2896	PP
4	2942	CP
5	2935	PP
6	2923	PP

2.10 Increased SS

We investigated a slightly thicker laminate with three more plies of SS PCR. We fabricated six specimens of 0.210-in tile with 46 plies of SS PCR. The targets had an areal density of 4.03 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 10.

Table 10. V_{50} testing with three additional SS plies.

Shot No.	Velocity (fps)	Result
1	2912	PP
2	2862	CP
3	2791	PP
4	2775	CP
5	2933	PP
6	2957	PP

The increased laminate thickness test series resulted in a V_{50} of 2826 fps (2 shot) with a 71-fps spread. This was below the acceptable V_{50} requirement; therefore, this laminate design was not considered for further testing.

2.11 CERCOM Powder Process Tile

CERCOM Inc.* (CERCOM) supplied samples of boron carbide (B_4C) tile that were produced using a hot pressing operation starting with a powder charge in the mold, which is the standard method of producing large billets of this material. We fabricated six specimens of 0.210-in tile with 46 plies of SS PCR. The targets had an areal density of 4.03 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 11.

Table 11. V_{50} testing with powder-processed tile.

Shot No.	Velocity (fps)	Result
1	2964	CP
2	2840	PP
3	2896	PP
4	2853	PP
5	3000	CP
6	2917	CP

The powder process tile test series resulted in a V_{50} of 2907 fps (4 shot) with a 111-fps spread. This result was consistent with the baseline test results.

2.12 CERCOM Tape Process Tile

CERCOM supplied samples of B_4C tile that were produced using a hot pressing operation starting with a tape-laid charge in the mold. The use of this method of tile fabrication will lower the cost of fabricating the production tile. We fabricated six specimens of 0.210-in tile with 46 plies of SS PCR. The targets had an areal density of 4.03 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 12.

The tape process tile test series resulted in a V_{50} of 3100 fps (2 shot) with a 55-fps spread. This test indicated that the tape process for producing tile has a positive effect on the ballistic performance of the armor system.

*CERCOM Inc., 991 Park Center Drive, Vista, CA 92083.

Table 12. V_{50} testing with tape-processed tile.

Shot No.	Velocity (fps)	Result
1	2739	PP
2	2811	PP
3	2899	PP
4	3046	PP
5	3073	PP
6	3128	CP

2.13 Increased Laminate Armor System

The areal density requirement of the armor system was increased from 4.0 to 4.8 psf. We investigated the increase by adding additional SS, and raising the minimum tile thickness from 0.210 to 0.230 in. We fabricated six specimens of 0.230-in tile with 64 plies of SS PCR. The targets had an areal density of 4.78 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 13.

Table 13. V_{50} testing with increased laminate armor system.

Shot No.	Velocity (fps)	Result
1	2866	PP
2	2928	PP
3	2958	CP
4	2965	CP
5	2966	PP
6	2943	CP

The increased laminate test series resulted in a V_{50} of 2948 fps (4 shot) with a 38-fps spread. For V_{50} testing, this increase in armor system areal density did not seem to have any effect on the armor system performance.

2.14 Increased Tile Armor System

The areal density requirement of the armor system was increased from 4.0 to 4.8 psf. We investigated the increase by increasing the tile thickness from 0.210

to 0.280 in and decreasing the laminate from 43 to 40 plies of SS. We fabricated six specimens of 0.280-in tile with 40 plies of SS PCR. The targets had an areal density of 4.79 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 14.

Table 14. V_{50} testing with increased areal density armor system.

Shot No.	Velocity (fps)	Result
1	2866	PP
2	2928	PP
3	2958	CP
4	2965	CP
5	2966	PP
6	2943	CP

The increased tile test series resulted in a V_{50} of 3002 fps (4 shot) with a 93-fps spread. The armor system seemed to increase in ballistic performance when the tile was increased.

2.15 Kevlar/SS Hybrid Armor System

Since the areal density requirement of the armor system was increased from 4.0 to 4.8 psf and the thicker tile test series produced a high V_{50}, we revisited the Kevlar/SS hybrid armor system. We fabricated six specimens of 0.280-in tile with 36 plies of SS PCR/1-ply Kevlar epoxy hybrid laminates. The targets had an areal density of 4.74 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 15.

The Kevlar/SS test series resulted in a V_{50} of 3020 fps (2 shot) with a 13-fps spread. This result was consistent with the baseline increased areal density test results.

2.16 Double-Process Laminate

During the original FAT testing, we noticed that some of the test specimens performed better than others. After investigation, we found that the specimens that performed better ballistically, had been processed in the autoclave twice due

Table 15. V_{50} testing with Kevlar/SS hybrid armor system.

Shot No.	Velocity (fps)	Result
1	2930	PP
2	3033	CP
3	2898	PP
4	3014	PP
5	3027	CP
6	2770	PP

to a vacuum bag malfunction. In order to investigate this phenomena, we fabricated six specimens of 0.230-in tile with 46 plies of SS PCR, and ran the targets through the autoclave twice. The targets had an areal density of 4.29 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 16.

Table 16. V_{50} testing with double-processed laminate.

Shot No.	Velocity (fps)	Result
1	2783	PP
2	2749	PP
3	2879	PP
4	2904	PP
5	3002	CP
6	2984	CP

The double-process laminate test series resulted in a V50 of 2944 fps (2 shot) with an 80-fps spread. These results did not prove that the double processing enhanced the ballistic performance of the armor system; therefore, no further investigation was warranted.

2.17 Kevlar/SS/Kevlar Hybrid Armor System

Past studies have shown that support of the ceramic material provides increased ballistic performance. We investigated a hybrid using KM2 fabric impregnated with vinyl-ester (VE) resin to provide support as well as ballistic resistance, SS to provide a tough middle layer, and KM2 polyurethane as a stiff ballistic back

face. We fabricated six specimens of 0.280-in tile with 4-ply KM2 VE/22-ply SS PCR/5-ply KM2 film stack hybrid laminates. The targets had an areal density of 4.87 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 17.

Table 17. V_{50} testing with Kevlar/SS/Kevlar hybrid armor system.

Shot No.	Velocity (fps)	Result
1	2774	PP
2	2851	PP
3	2970	PP
4	3003	CP
5	2790	PP
6	2832	PP

The Kevlar/SS/Kevlar test series resulted in a V_{50} of 2986 fps (2 shot) with a 33-fps spread. These results did not prove that the Kevlar/SS/Kevlar hybrid enhanced the ballistic performance of the armor system, no further investigation was warranted. The result of this testing is the current SAPI design of 0.270 ± 0.020 in B_4C on 45 plies of SS, processed at 250 psi and 250 °F for 2 hr.

3. Further SAPI Optimization Efforts

At this point, we investigated a non-Spectra-based laminate backing. We chose two contending materials: KM2 film stacked with polyethylene and KM2 Mark III supplied by DuPont. This testing was performed at Simula Technologies Inc.* ballistic test facilities during August 2000.

3.1 KM2 Polyethylene Film Stack Laminate

The use of the KM2 600 denier (film stacked with polyethylene) would provide a stiff, supportive yet ballistically viable composite backing, so we tested a KM2 polyethylene film stack laminate. We fabricated six specimens of 0.272-in tile with 22 plies of KM2 (850 denier style 705) and 23 plies polyethylene film

*Simula Technologies Inc., is the parent organization of Simula Safety Systems, Inc. (a wholly owned subsidiary).

(0.001 in). The targets had an areal density of 4.78 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 18.

Table 18. V_{50} testing with 22-ply KM2/polyethylene film-stacked backings.

Shot No.	Velocity (fps)	Result
1	2746	PP
2	2938	PP
3	2901	PP
4	3006	PP
5	3142	CP
6	3079	PP

The 22-ply KM2/polyethylene test series resulted in a V_{50} of 3110 fps (2 shot) with a 63-fps spread.

3.2 KM2 Mark III Laminate

The use of the KM2 (Style 705) Mark III will provide a stiff, supportive, yet ballistically viable, composite backing. We tested a KM2 Mark III laminate and fabricated six specimens of 0.272-in tile with 21 plies of KM2 (850 denier style 705) Mark III material supplied by DuPont. The targets had an areal density of 4.81 psf. These specimens were tested for V_{50} with threat A on 28-ply KM2 600 denier backings. The results for this series are shown in Table 19.

Table 19. V_{50} testing with 21-ply KM2 Mark III backings.

Shot No.	Velocity (fps)	Result
1	2831	PP
2	2918	CP
3	2853	PP
4	2884	PP
5	2900	PP
6	2843	PP

The 22-ply KM2 Mark III test series resulted in a V_{50} of 2909 fps (2 shot) with an 18-fps spread.

4. Conclusions

After testing various laminate backings, the all-SS option proved to be the most desirable from a cost and performance standpoint. By the time we began investigating the KM2 film stack and KM2 Mark III options, we had already identified a new ceramic material supplied by M Cubed Technologies Inc. of Newark, DE. This new ceramic material is a "reaction bonded" silicone carbide that can be produced to tighter tolerances at a much lower cost compared to the hot-pressed B_4C material. We were directed and funded to perform another MANTECH effort (delivery order 9)[1] to investigate the use of this new ceramic material for the Interceptor program. Based on this information, the baseline B_4C/SS armor system remains as 0.270 ± 0.020-in B_4C on 45 plies of SS PCR bonded at 25 psi and 250 °F for 2 hr.

[1]Mears, J. A., R. F. Monks, R. Wolffe, and J. F. Mackiewicz. "Interceptor Small Arms Protective Insert (SAPI) MANTECH Product Enhancement Test Report II." ARL-CR-488, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, February 2002.

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This report summarizes the work performed by Specialty Plastics Products of Pennsylvania Inc. and their subcontractor, Simula Safety Systems Inc., under the Manufacturing Technology (MANTECH) program sponsored by the U.S. Army Materiel Command and executed by the U.S. Army Natick Soldier Center. The objective of this effort was to investigate armor materials and processes that could potentially provide cost reductions to the multi-Service Interceptor Small Arms Protective Inserts (SAPI).

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